

Modeling Separated Flows Using Stationary Discrete Vortices

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Abstract

In many technological units (heating furnaces, kilns, aspiration hoods, etc.), a provision is made to include open ports through which undesirable air can flow. Air curtains have been widely applied to reduce the air flow rate by increasing the drag in these ports. However, this method of reducing the flow rate results in rather high operational cost due to unavoidable loss of electrical energy through air-curtain fans. Structural elements installed in front of the port inlet can provide an alternative. These structural elements ensure the drag increase without shutting off the effective cross section of the ports (in order to ensure implementation of technological operations of aggregate loading, displacement of different-type manipulators, or transport vehicles) and can be implemented with minimum cost. This study objective is to develop a method of mathematical modeling of separated flows upstream of suction slot openings within the SDVM (The discrete vortex method application is known in the stationary set-up framework). With use of discrete vortexes method in stationary statement, mathematical modeling method of detached flow on the input to the flat canals is constructed and discussed. The problem about detached flow on the input to the flat canal with screen is solved. Validity and adequacy of received results are demonstrated by the comparison with calculations, according to the method of N.E. Zukovsky and by experimental data. The developed method of mathematical modeling and computing algorithm of its realization may be used for detection of current available line, velocity field and form loss coefficient of input to the suction ducts, equipped by arbitrary system of thin screens.

Keywords: detached flows, discrete vortexes method, form loss coefficient

1. Introduction

The most exact data about flows in action spectrums of soaking-up openings are necessary for industrial ventilation tasks solving (Logachev, 2005-2014; Dorocenko, 2006).

There is ideal incompressible liquid analyzed (Logachev, 1995; Anzheurov, 2003). A vortex is separating from the sharp boundary edge and so-called free flow line is originating from the edge in the position unknown in advance. Traditionally this problem can be solved using the complex variable theory and ideal liquid jet theory methods (Averkova, Logachev, 2013). It is assumed that the velocity on the free flow line is constant. Using such methods ensures the most accurate results. There is an analytical solution obtained in some of the simplest cases. The problem often resolves oneself into quite lengthy non-linear equations with coefficients of unknown variables in the form of Cauchy type integrals. In the general case when a multiply connected flow region or, all the more, a three-dimensional space is considered solving the problems using the methods above is impossible.

The discrete vortex method application is known in the stationary set-up (SDVM) (Belotserkovsky1992; Lifanov, 2003; Logachev, 2006-2014) to solve problems of a separated flow of ideal incompressible liquid upstream of a round continuous tube (Logachev, 2004). The problem was solved in the axially symmetric set up with discrete vortex rings used as discrete vortices. A clearer boundary of the free streamline surface would be obtained by placing a free vortex ring on the sharp edge.

This study objective is to develop a method of mathematical modeling of separated flows upstream of suction slot openings within the SDVM framework.

2. Materials and Methods

As an example, we considered a problem of a separated flow of ideal incompressible liquid upstream of a screened plane wall suction port (Figure 1) previously solved by various methods.

The following symbols were introduced: N is the number of bound vortices of the upper boundary (above OX axis); N_s is the number of free vortices of the upper boundary. The vortex lying on sharp screen edge C is considered to be a free one which follows from the theorem set forth in [15]: the bound vortex intensity (circulation) at the flow separation point is equal to zero. Bound vortices were also positioned at the boundary fracture points. There were reference points positioned between the bound vortices.

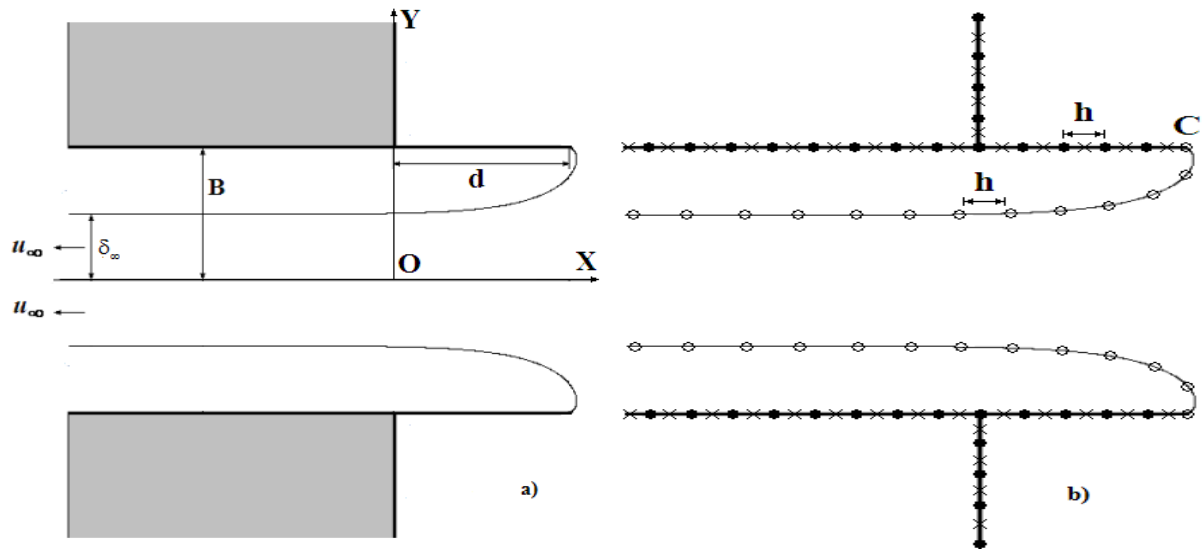


Figure 1. Regarding the problem set-up: a) physical flow area; b) range boundary discretization: (● is for bound vortices, ○ is for free vortices, × is for reference points)

Point $\xi^k (\xi_1, \xi_2)$ is the bound vortex position point; $x^p (x_1, x_2)$ is the reference point. The action on point x^p (velocity at this point) by the vortex of a single circulation located at point ξ^k along the unit vector $\vec{n} = \{n_1, n_2\}$ is determined from the formula:

$$G(x^p, \xi^k) = \frac{1}{2\pi} \cdot \frac{(x_1 - \xi_1)n_2 - (x_2 - \xi_2)n_1}{(x_1 - \xi_1)^2 + (x_2 - \xi_2)^2} \tag{1}$$

This vortex action on point x^p is given by

$$v_n(x^p) = G(x^p, \xi^k) T(\xi^k), \tag{2}$$

where $T(\xi^k)$ is a circulation of the vortex located at point ξ^k ; $v_n(x^p)$ is the velocity at point x^p along the unit vector \vec{n} .

With the boundary discretization method described above the number of bound vortices is equal to the number of reference points. Since the range boundary is symmetric around OX axis and this axis is impermeable the circulation of symmetric vortices will be inverse:

$$T(\xi^k) = -T(\xi^{k+N}), \text{ where } k = \overline{1, N}. \tag{3}$$

Fulfillment of this condition will automatically result in the non-circular flow condition (the sum of circulations of all vortices is equal to zero).

It was assumed that circulation of vortices on the required free flow line is constant and equal to $[\gamma]$. The distance between free vortices is a constant value equal to h . The first approximation for the free flow line was chosen as follows. The first three vortices were position in parallel to OY starting from the sharp edge while the rest of the vortices were positioned in parallel to OX .

The resultant action of all vortices on reference point x^p along the outward normal is given by:

$$\begin{aligned}
 v_n(x^p) &= \sum_{q=1}^N G(x^p, \xi^q) T(\xi^q) - \\
 &- \sum_{q=N+1}^{2N} G(x^p, \xi^q) T(\xi^{q-N}) + \gamma \sum_{k=1}^{N_s} G(x^p, \zeta^k) - \\
 &- \gamma \sum_{k=N_s+1}^{2N_s} G(x^p, \zeta^k) = \\
 &= \sum_{q=1}^N (G(x^p, \xi^q) - G(x^p, \xi^{q+N})) T(\xi^q) + \\
 &+ \gamma \sum_{k=1}^{N_s} (G(x^p, \zeta^k) - G(x^p, \zeta^{k+N_s})), \quad (4)
 \end{aligned}$$

where ζ^k is a free vortex position point.

Since $v_n(x^p) = 0$ at all reference points, that is, the impermeability condition is fulfilled, expression (4) will be converted as follows:

$$\begin{aligned}
 \sum_{q=1}^N (G(x^p, \xi^q) - G(x^p, \xi^{q+N})) T(\xi^q) &= \\
 = -\gamma \sum_{k=1}^{N_s} (G(x^p, \zeta^k) - G(x^p, \zeta^{k+N_s})). \quad (5)
 \end{aligned}$$

When p is changed between 1 and N expression (5) becomes a set of linear algebraic equations (SLAE) with N unknown variables $T(\xi^1), T(\xi^2), \dots, T(\xi^N)$. By solving this set using the Gaussian method with pivoting and determining unknown circulations of bound vortices we'll be able to compute the velocity at any point $x(x_1, x_2)$ of the range along any given direction from the formula:

$$\begin{aligned}
 v_n(x) &= \sum_{q=1}^N (G(x, \xi^q) - G(x, \xi^{q+N})) T(\xi^q) + \\
 &+ \gamma \sum_{k=1}^{N_s} (G(x, \zeta^k) - G(x, \zeta^{k+N_s})). \quad (6)
 \end{aligned}$$

If the distance from point x to the vortex at point ξ is less than $h/2$ then $G(x, \xi)$ is given by:

$$G(x, \xi) = \frac{r}{\pi h} \cdot \frac{(S_1 - \xi_1)n_2 - (S_2 - \xi_2)n_1}{(S_1 - \xi_1)^2 + (S_2 - \xi_2)^2}, \quad (7)$$

where $S_1 = \frac{h}{2r}(x_1 - \xi_1) + \xi_1$; $S_2 = \frac{h}{2r}(x_2 - \xi_2) + \xi_2$; $r = \sqrt{(x_1 - \xi_1)^2 + (x_2 - \xi_2)^2}$.

The second approximation for the free flow line was chosen as follows. There is a flow line plotted from sharp edge C in the defined velocity field using the following formulas:

$$x = x' + v_x \Delta t, \quad y = y' + v_y \Delta t, \quad (8)$$

where Δt is a quite small time increment (e.g. $\Delta t = 0.0001$); (x', y') is the previous position of the point on the flow line; (x, y) is the previous point; v_x, v_y are found from (6) at $\vec{n} = \{1; 0\}$ for v_x and $\vec{n} = \{0; 1\}$ for v_y . As soon as the distance between point (x, y) and the sharp edge becomes equal to h a free vortex is placed at this point, i.e. it will be the second approximation for this free flow line point. Then, a flow line is plotted again using (8) until the distance between (x, y) and the previous position of the free vortex becomes equal to h . A free vortex is placed at this point and so on.

After defining the second approximation for the free flow line there should be set of equations (5) resolved again and bound vortex circulations determined. Then, the third approximation is made for the free flow line using formulas (6)-(8) etc. This iteration process is repeated until the difference between the previous and next positions does not exceed the given accuracy.

Since the range boundaries “break” at some distance from the suction port a situation occurs when the free flow line starts lifting up (for upper part of Figure1), i.e. its Y-coordinate starts increasing. That is why in this case y-coordinate is fixed for all other points and is equal to the maximum decrease point Y-coordinate.

The word description of the computational algorithm built using design relations (1)-(8) is as follows.

1. There are matrixes of coordinates of reference points $kt[1..N,1..2]$; coordinates of bound vortices $pv[1..N,1..2]$; coordinates of free vortices $sv[1..N,1..2]$ formed.

a. For the upper screen:

$$\begin{aligned} kt[i,1] &= d - h \left(i - \frac{1}{2} \right); \quad kt[i,2] = B; \\ pv[i,1] &= kt[i,1] - \frac{h}{2}; \quad pv[i,2] = B; \\ i &= \overline{1, N_1}, \quad \text{where } kt[N_1,1] = \frac{h}{2}; \quad pv[N_1,1] = 0. \end{aligned}$$

b. For the upper vertical wall:

$$\begin{aligned} kt[i,1] &= 0; \quad kt[i,2] = B + h \left(k - \frac{1}{2} \right); \\ pv[i,1] &= 0; \quad pv[i,2] = kt[i,2] + \frac{h}{2}; \\ i &= \overline{N_1, N}; \quad \text{where } kt[N,2] = kalibr - \frac{h}{2}; \end{aligned}$$

$kalibr$ is the vertical wall length (divisible by the suction port width B);

$$k = 1, 2, \dots \text{ until } \left(kt[N,2] - kalibr + \frac{h}{2} \right) < 0.000001.$$

c. For the range boundary symmetric around OX :

$$\begin{aligned} kt[i,1] &= kt[i-n,1]; \quad kt[i,2] = -kt[i-n,2]; \\ pv[i,1] &= pv[i-n,1]; \quad pv[i,2] = -pv[i-n,2]; \end{aligned}$$

where $i = \overline{N+1, 2N}$.

d. For the upper free flow line:

$$\begin{aligned} sv[i,1] &= d; \quad sv[i,2] = b - h(i-1); \quad i = \overline{1, 3}; \\ sv[i,1] &= d - h(i-3); \quad sv[i,2] = b - 2h; \quad i = \overline{4, k_2}; \end{aligned}$$

where k_2 is an integral part of $kalibr / h$; $N_s = i - 1$.

e. For the lower free flow line:

$$\begin{aligned} sv[i,1] &= sv[i - N_s, 1]; \quad sv[i,2] = -sv[i - N_s, 2]; \\ i &= \overline{N_s + 1, 2N_s}. \end{aligned}$$

2. Forming a matrix of coefficients of unknown variables of SLAE (5):

$$\begin{aligned} kof[p, q] &= Skor(kt[p], pv[q], evn) - \\ &\quad - Skor(kt[p], pv[q+n], evn); \end{aligned}$$

where $p = \overline{1, N}$; $q = \overline{1, N}$; $env[1..2]$ are outward normal coordinates:

$$\begin{aligned} env[1] &= 0; \quad env[2] = -1 \quad \text{at } kt[p, 2] = B; \quad env[1] = 0; \quad env[2] = 1 \quad \text{at } kt[p, 2] = -B; \\ env[1] &= -1; \quad env[2] = 0 \quad \text{at } kt[p, 1] = 0; \end{aligned}$$

$Skor(kt[p], pv[q], env)$ is a velocity along env vector direction at point $kt[p]$ induced by the single circulation vortex located at point $pv[q]$. It is calculated using formulas (1), (7).

3. Forming a column of free terms for SLAE (5):

$$pr[p] = -SvG \sum_{k=1}^{N_s} (Skor(kt[p], sv[k], evn) - Skor(kt[p], sv[k + N_s], evn)),$$

where $p = \overline{1, N}$; SvG is a circulation of vortices on the free flow line.

4. Solving SLAE

$\sum_{q=1}^N kof[p, q] circ[q] = pr[p]$; $p = \overline{1, N}$ using the Gaussian method with pivoting and determination of the

matrix of circulations of bound vortices $circ[1..N]$ at the upper boundary. Accordingly, for the lower

boundary: $circ[i] = -circ[i - N]$, $i = \overline{N + 1, 2N}$.

5. Forming coordinates of the next approximation for the free flow line:

- There is an initial point of the flow line given $x[1] = sv[1, 1]$; $x[2] = sv[1, 2]$.
- There is an increment in the flow velocity direction made, i.e. there are coordinates calculated:

$$x[i] = x[i] + chag \left(\sum_{q=1}^{2N} circ[q] Skor(x, pv[q], evn) + SvG \sum_{q=1}^{N_s} (Skor(x, sv[q], evn) - Skor(x, sv[q + N_s], evn)) \right),$$

where $i = \overline{1, 2}$; $evn[1] = 1$; $evn[2] = 0$ at $i = 1$ and $evn[1] = 0$; $evn[2] = 1$ at $i = 2$; $chag = 0,0001$ is time increment.

c. As soon as the distance from point x to the previous point of the free flow line is $\sqrt{(x[1] - sv[i-1, 1])^2 + (x[2] - sv[i-1, 2])^2} \geq h$ there are coordinates of the next approximation determined

for the free flow line coordinates $psv[i] = x$.

d. If the flow line point Y-coordinate exceeds the previous point Y-coordinate proceed to step e) otherwise proceed to step b). The count interruption condition: $x[1] < sv[N_s, 1]$.

e. There are the free flow line points determined:

$$psv[i, 1] = psv[i-1, 1] - h; \quad psv[i, 2] = x[2].$$

The count interruption condition: $psv[i, 1] < sv[N_s, 1]$.

f. Old coordinates of the free flow line are changed for new ones

$$sv[i] = psv[i]; \quad sv[i + N_s, 1] = psv[i, 1]; \quad sv[i + N_s, 2] = -psv[i, 2],$$

where $i = \overline{1, N_s}$.

6. Then proceed to step 3, i.e. determine the new approximation for the free flow line. This cycle is repeated as long as $|db - pv[N_s, 2]| > 0.0001$, where $db = sv[N_s, 2]$ is Y-coordinate of the previous position of N_s point of the free flow line.

After the free flow line boundary has been defined its coordinates and circulations of bound vortices will be written to a file. Then this data can be used to determine the field of velocities. The velocity at the given point $x(x[1], x[2])$ along the given direction $evn(evn[1]; evn[2])$ will be determined from the formula:

$$v = \sum_{q=1}^{2N} circ[q] Skor(x, pv[q], evn) + SvG \sum_{q=1}^{N_s} (Skor(x, sv[q], evn) - Skor(x, sv[q + N_s], evn)).$$

3. Results

Using the developed software program there were dimensionless velocity profiles ($u_x/u_\infty; u_y/u_\infty$) and free flow line coordinates calculated. For convenience of comparison of calculations made with various methods they are represented in another system of coordinates (Figure 2).

Continuous lines on all figures denote calculations made using The Zukovsky method while dotted and dash-dotted lines demote calculations made using the SDVM. As seen, the velocity and free flow line coordinates actually coincide. The biggest difference for the horizontal velocity component is observed in section $x=0.8$ but it does not exceed 2% versus calculations made using the Zukovsky method. The discretization interval in calculations made using the DVM is $h=0.0125$, u_∞ was assumed to be the velocity on the suction axis 2 gauges away from the suction port.

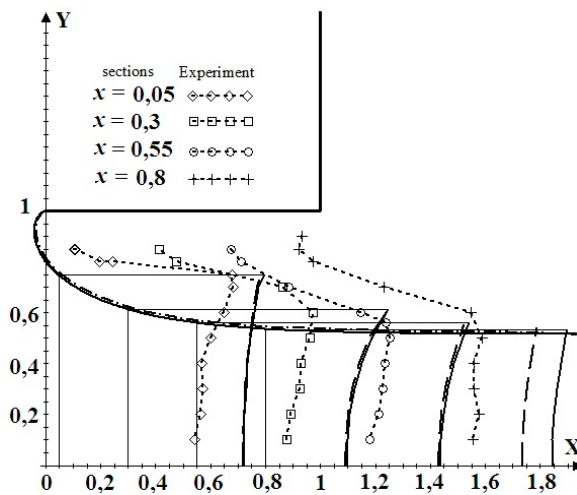


Figure 2. Free flow line and horizontal velocity component profiles

The vertical wall length and the distance of the last free flow line point from the suction port is equal to 8 gauges (8C).

The ratio of the difference of velocity u_∞ and average slot velocity $u_\infty \delta_\infty / B$ to the average velocity is $\Delta u = B / \delta_\infty - 1$ which was used as the local drag factor criterion in Chapter 4. Calculation of Δu using the discrete vortex method demonstrates better conformance to the experimental data for the local drag factor ζ than in case with The Zukovsky method (Figure 3).

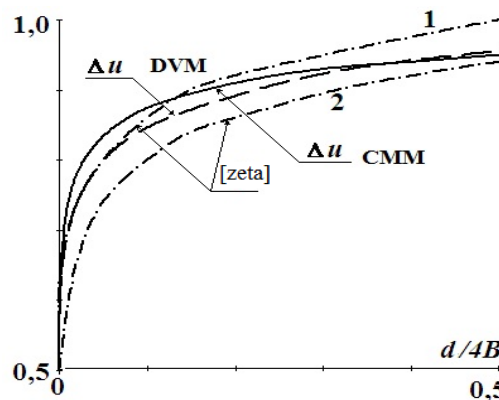


Figure 3. Variation in the local drag factor upstream of a flat pipe (ζ) and in the jet separation velocity (Δu) with increase in the offset length ($d/4B$): dash-dotted lines denote experimental data by I.E. Idelchik, 1977 (curve 1 is for the relative tube wall thickness $\delta/D_g = 0$; curve 2 is for $\delta/D_g = 0.004$)

4. Discussion

Applied problems of industrial aerodynamics most often focus on reducing the drag of a suction slot (Khanzhonokov, 1959; Nosova 1959; Idelchik, 1977). But increasing this drag is equally important. First of all, it relates to the practical reducing of the intake of the gaseous medium through openings when there are no options of sealing left. One of the technical means to reduce unwanted air inflows is to use special screens which increase the drag and reduce the flow coefficients of air entering through minimized openings. These tasks can occur, say, for specialists engaged in confinement of harmful emissions by local exhaust ventilation (Logachev, 2005), as well as in various heat and power plants.

The ideal fluid theory, in particular the method by N.E. Zhukovsky, was used in the study of separated flows at the inlet into flat channels (Logachev, 2010) due to the fact that it allows determining not only the kinematic characteristic of the flow, but also the deterministic boundary of the flow. For example, the jet thickness, which is used to estimate the air drag at the inlet into holes.

Using the discrete vortex method in the non-stationary set up (NDVM) (Belotserkovsky, Lifanov 1995; Logachev, 2005-2010) enables plotting free lines and streamline surfaces. However, according to numerical experiments for problems concerning suction spectra of exhaust slots, jet contraction δ_{∞} at a considerable distance from the suction port remains virtually unchanged while some geometric dimensions are changing. In addition, this value pulsates in time and needs to be averaged over time. Therefore using the NDVM to analyze δ_{∞} , determine the boundaries of separated flows and the relation of these values with air drag of suction inlets presents a certain problem.

Novelty of this work is the development of the method of the detachable current on the entrance to the soaking-up channels with use of stationary discrete vortexes. This method allows to define the border of a detachable current and compression coefficient of the stream which is necessary for determination of the local resistance coefficient. Simulating experiment with use of the method of simulation of RANS (Reynolds Averaged Navier-Stokes) from the Fluent software package didn't allow to define such distinct border of the jet separation. The method developed on the basis of stationary discrete vortexes gives the results which correspond more to the natural experiment.

5. Conclusion

Thus, the mathematical model of separated flows elaborated based on the SDVM allows for obtaining an adequate flow pattern and its application will enable resolving a number of problems of separated flow air mechanics. Further development of this method will consist in the accounting of the thin closed bodies in a range of operation of exhaust channels. It will allow to operate a stream separation on an entrance to soaking-up channels. It is planned to consider axisymmetric tasks also. In particular to investigate influence of thin screens on coefficient of local resistance of an entrance to round soaking-up channels. It is necessary to specify interrelation of coefficient of local resistance and size of compression of a stream. For this purpose it is necessary to make natural experiment. And, at last, it represents great scientific interest to consider a stream separation from sharp edges of the soaking-up channel in full three-dimensional statement.

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